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ACTIVATION AND INITIAL TEST OPERATIONS
LARGE ROCKET ENGINE - THRUST CHAMBER TEST FACILITIES

By

D. H. Clark

Prepared for

National Aeronautics and Space Administration

Contract NAS 3-2555

AEROJET-GENERAL CORPORATION

SACRAMENTO, CALIFORNIA

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TECHNOLOGY REPORT

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ABSTRACT

Testing of the thrust chamber assembly for the NASA M-1 Engine at a vacuum equivalent thrust level of 1.5 million lbf imposed several new facility requirements and created unique testing problems. This report describes the unusual aspects of facility activation, the problems encountered, the corrective actions taken, and the initial operation of the test facilities.

TABLE OF CONTENTS

		Page
I.	SUMMARY	1
II.	INTRODUCTION	1
III.	FACILITY DESCRIPTION	1
IV.	FACILITY ACTIVATION AND DESIGN VERIFICATION	5
	A. INTEGRATED SYSTEM DYNAMICS EFFECTS	6
	B. THRUST MEASUREMENT SYSTEM	9
	C. LIQUID OXYGEN FLOWMETER CALIBRATION	12
	D. CONTROLS SYSTEM - COMPUTER CHECKOUT	12
	E. COLD FLOW TESTS	13
	F. GASEOUS AND LIQUID HYDROGEN MIXER SYSTEM	16
	G. FACILITY THRUST CHAMBER VALVES	16
	H. OTHER PROBLEMS	19
	1. Hydrogen Lead Gas	19
	2. High Pressure Leakage in Large Diameter Cryogenic Lines	19
	3. Sound Level	19
V.	THRUST CHAMBER ASSEMBLY TESTING EXPERIENCE	20
	A. START TRANSIENT	20
	B. STEADY-STATE OPERATION	22
	C. INDUCED INSTABILITY AND RECOVERY	22
	D. SHUTDOWN TRANSIENT	24
VI.	TEST OPERATIONS EXPERIENCE	24
VII.	FACILITY EXPERIENCE	24
	A. FLOW-CONTROL VALVE GALLING	24

TABLE OF CONTENTS (CONT)

			Page
	B.	HIGH-PRESSURE GAS VALVES	25
	C.	CRYOGENIC VALVES	25
	D.	LARGE HIGH-PRESSURE FLANGE MAKE-UP	25
	E.	FAIL-SAFE MANIFOLDS	26
	F.	CROSS CONNECT POTENTIAL, ELECTRICAL CONTROLS	26
	G.	FLUORINE CHECK VALVES	26
	H.	CABLE PROTECTION	26
	I.	FLUID DECELERATION EFFECTS	27
VIII.	CONCLUSIONS		27

LIST OF FIGURES

No.	Title	Page
1	Rear View of Test Stand H-8 During Firing	2
2	Front View of Test Stand H-8	3
3	Schematic Diagram of Test Stand H-8 Propellant and Thrust Measuring Systems	4
4	Line Dampers of Test Stand H-8	10
5	Gaseous and Liquid Hydrogen Mixer Section	17
6	Critical Parameter Plots	21

LIST OF TABLES

No.	Title	Page
I	Resultant Changes of Damper Study	8
II	Cold-Flow Test Summary	14

I. SUMMARY

The testing of the thrust chamber assembly for the NASA liquid oxygen/liquid hydrogen M-1 Engine at a 1.5-million lbf vacuum-equivalent thrust level presented a challenging problem because of the size of the thrust chamber assembly and the serious consequences of test facility malfunction. A conservative approach to testing was adopted; attention was concentrated on known or anticipated critical areas of test facility design, and a step-by-step checkout was used to ensure successful facility operation during the thrust chamber assembly tests. Through this sequential checkout procedure, the problems encountered with the functioning of the facilities and instrumentation were resolved before proceeding to the next step, and the operation of all systems was confirmed before actual testing was begun. This approach led to reliable facility operation during the hot-firing tests.

II. INTRODUCTION

Testing objectives for the M-1 thrust chamber assembly were to determine the performance and stability characteristics of several injector configurations over a broad band of mixture ratio and fuel inlet-temperature conditions using an uncooled, ablative-lined combustion chamber.

To minimize the likelihood of malfunction during the tests, the most conservative approach possible was used for control of the starting and shutdown transients. Evolution of a thrust chamber starting transient with this degree of conservatism was an appreciable task. Ultimately, a system that commanded 50 control functions was developed to control the starting transient. This control system required that completion of 20 analog and event functions occur in proper sequence during the start transient to ensure that a satisfactory start was achieved. Also, during this period, events and functions were monitored which could instigate a "fail-safe" shutdown if established limits were exceeded.

The testing was accomplished on Test Stand H-8 in the H-Zone complex of Aerojet-General's Sacramento Plant Test Operations. These facilities are described briefly in this report.

III. FACILITY DESCRIPTION

Test Stand H-8 was selected as the site for the M-1 thrust chamber assembly tests. Two general views of this facility are shown in Figures 1 and 2. The propellant supply and feed system for this test stand, shown schematically in Figure 3, consists essentially of a parallel liquid oxygen/liquid hydrogen high-pressure system rated at 2475 psi under cryogenic conditions. The liquid hydrogen supply system is vacuum-jacketed, including a 25,000 gal storage vessel capable of supplying propellant for a test duration of approximately 22 sec. Propellant supply lines are primarily 14.-in. in

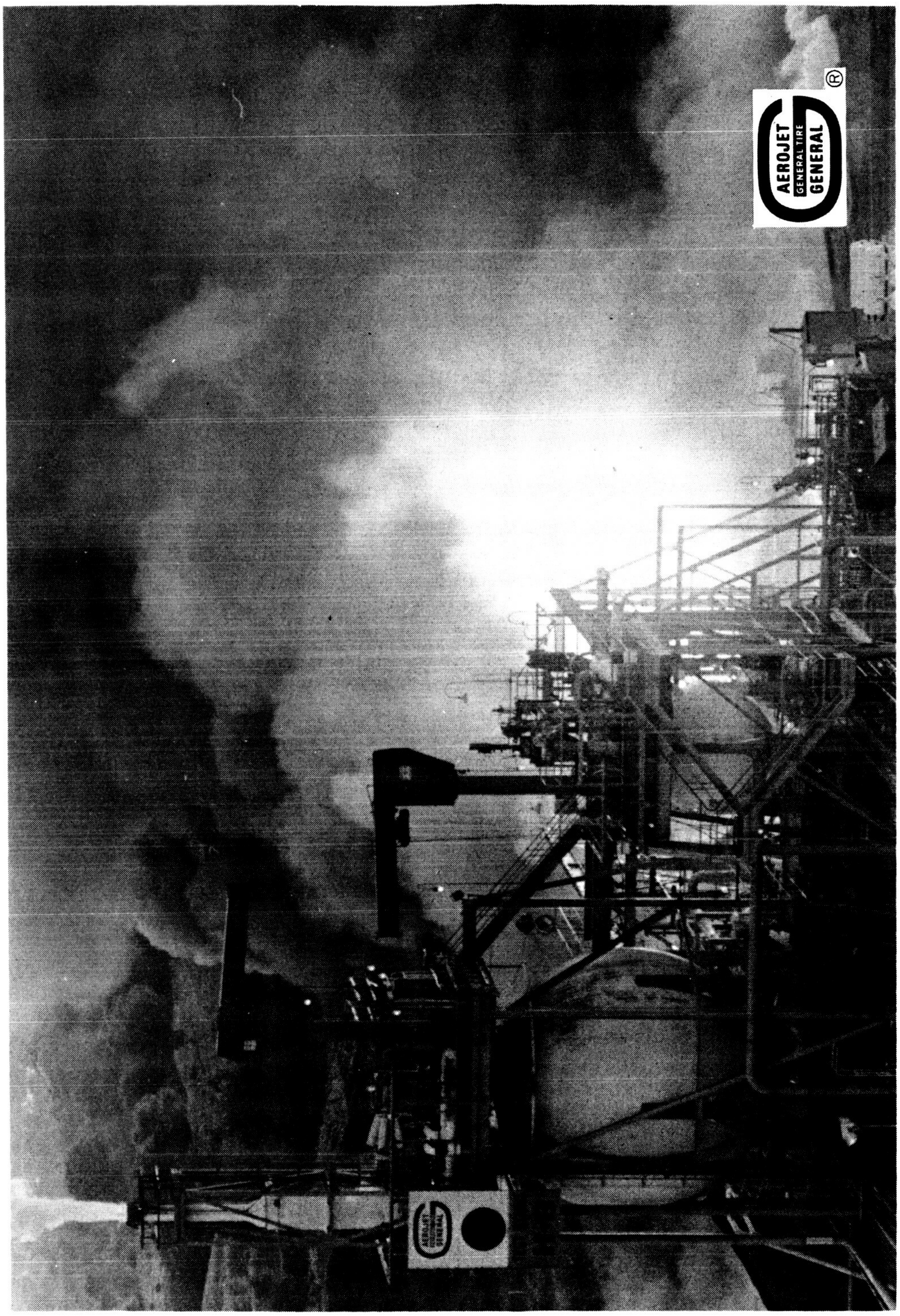

Figure 1. Rear View of Test Stand H-8 During Firing

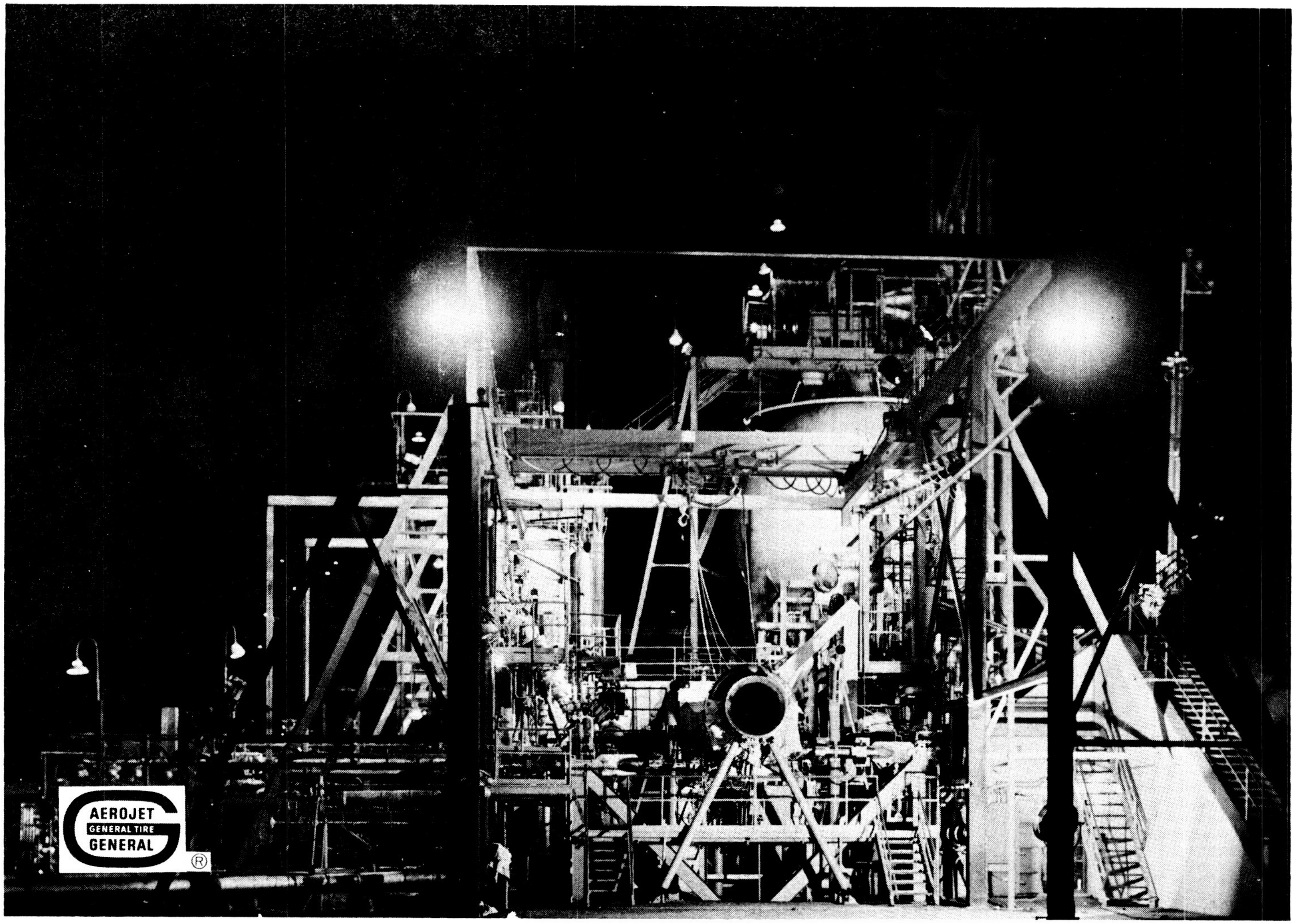

Figure 2. Front View of Test Stand H-8

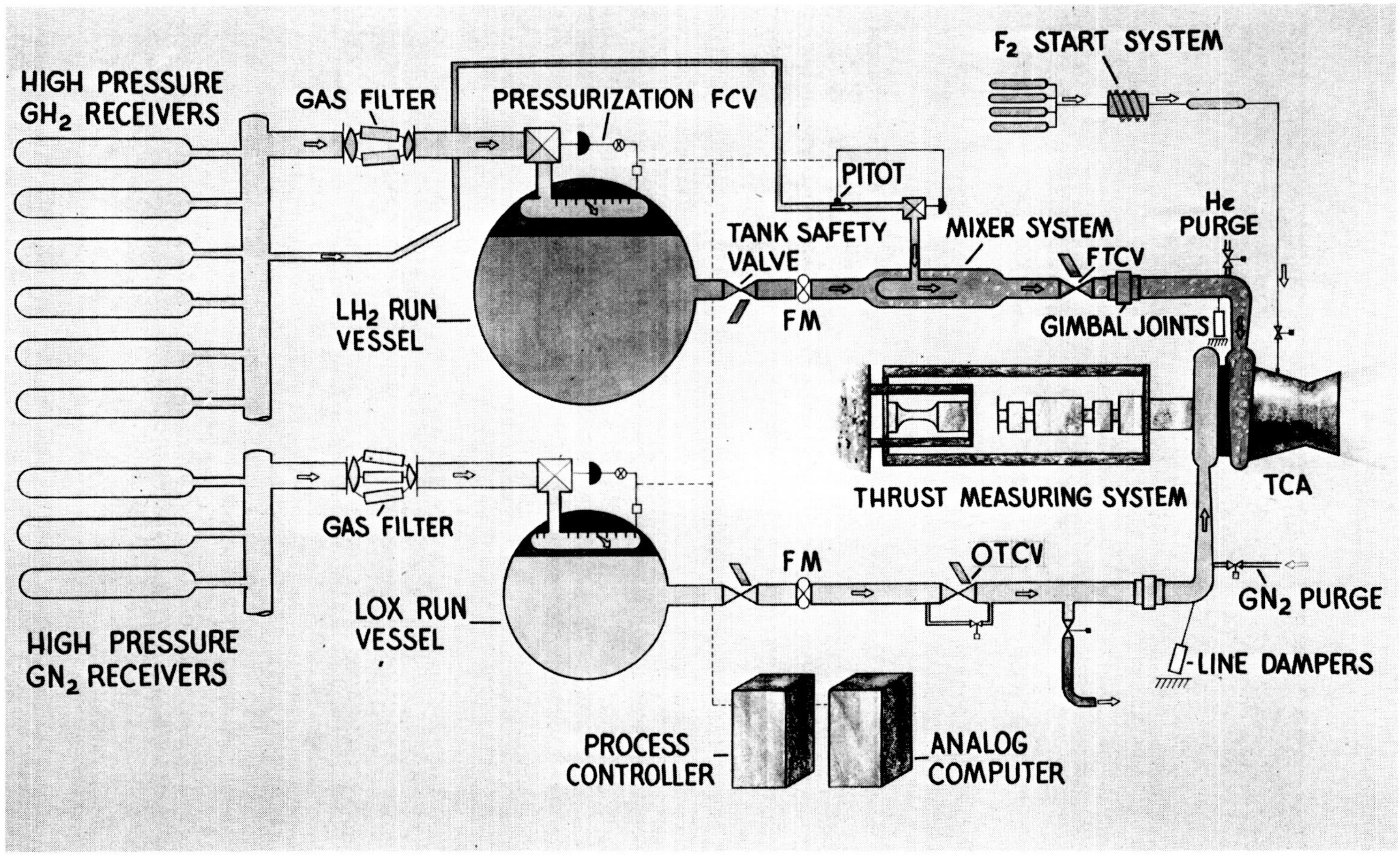

Figure 3. Schematic Diagram of Test Stand H-8 Propellant and Thrust Measuring Systems

diameter and contain a tank safety valve, a flowmeter, a facility thrust-chamber valve, and flexible joints near the thrust chamber assembly inlet. A high-pressure gaseous nitrogen system is used to pressurize the liquid oxygen tank and a gaseous hydrogen system is used to pressurize the liquid hydrogen tank. These pressurization systems, which include manifolded high-pressure receivers and hydraulic servo-controlled, pressure-regulating valves, are rated at 3500 psig for gaseous hydrogen and 5000 psig for gaseous nitrogen.

The fuel system also has a gaseous hydrogen injection and mixing system to warm the liquid hydrogen flow for uncooled combustion chamber tests. This system is used not only to simulate the heating that normally occurs within the tubes of a regeneratively-cooled, prototype chamber, but also to vary the fuel inlet temperatures for the determination of combustion instability boundary conditions.

The final ignition system design makes use of gaseous fluorine at 800 psi for hypergolic ignition with the hydrogen lead gas in the combustion chamber. The fluorine is supplied in commercial "K" bottles at 400 psi, and is condensed to liquid fluorine using liquid nitrogen. The liquid fluorine then is revaporized to pressurize the start tank to 800 psig.

Other secondary propellant systems are provided for bleed-in, gaseous nitrogen and gaseous hydrogen purging, hydraulic and pneumatic valve actuation, and off-stand cryogenic propellant storage and transfer.

The thrust-measuring system is designed to support the M-1 thrust chamber assembly horizontally. This system has a single load cell rated at 1.5M lb to measure thrust. The system also is equipped with an integrally-mounted calibration system having an identical load cell.

Functioning of the hardware and test facilities is controlled from a remotely located control room having an electronic process controller coupled with a manually operated control console. This control room has available approximately 400 instrumentation channels.

IV. FACILITY ACTIVATION AND DESIGN VERIFICATION

Activation of Test Stand H-8 followed a normal pattern in that system cleanliness inspections and individual component performance evaluations were the first steps to be taken. After the system had been inspected and individual component performance evaluated, verification of the entire system was begun. Major emphasis during the verification phase was placed on performance of critical or unique systems and functions. Subsequent paragraphs describe the systems and functions in this category and discuss the degree of concern, the problems involved in systems operation, and the acceptable solutions.

A. INTEGRATED SYSTEM DYNAMICS EFFECTS

A dynamics analysis of the integrated facilities and test hardware was of prime concern in the design evaluation of the H-8 facility systems. This emphasis on dynamics analysis was prompted by the problems encountered during the activation of Test Stand C-9, an interim vertical test stand for the M-1 thrust chamber assembly. The first full-scale thrust chamber assembly test using this stand resulted in a malfunction which damaged the hardware and test stand. All systems of the H-8 test complex were re-evaluated based upon recorded transient data from the thrust chamber assembly test on Test Stand C-9, and upon special studies which were made to determine the maximum expected transient and steady-state loads. The H-8 Test Stand Analysis included the combined structural, hydraulic and controls dynamics effects on the system.[(1)] The re-evaluated systems were the propellant feed system, the thrust measurement system, and the propellant pressurization system. Specific loading conditions included maximum thrust transient, maximum propellant flow transients, maximum pressurant-gas flow transients and maximum steady-state loading.

Computer techniques were used extensively in the design analysis both to determine the normal and abnormal loading conditions and to analyze the transient and steady-state response of the integrated system to predicted forcing functions.

The basic approach used for the dynamics analysis was to develop a mathematical analog for each of the major systems and to computerize the resultant models. The models then were subjected to a series of forcing functions which were determined from initial test data obtained during Test Stand C-9 tests and from the data derived through the computer model studies. Specific models included a propellant feed system hydraulic analog, a pressurant system hydraulic analog, a propellant feed system and thrust chamber assembly structural analog, a thrust measurement system structural analog, thrust chamber assembly combustion analog, and a controls system analog. Maximum malfunction loads also were determined for broken-line propellant acceleration loads and for maximum water-hammer forces. The steady-state random vibration energy expected during actual tests was predicted from recorded spectral density data of Apollo and Titan tests which had been scaled to relate the mass and energy of the various systems.

The reaction of the propellant piping to water-hammer and fluid acceleration loads caused by broken lines was of initial concern. The interaction between the propellant piping and the thrust measurement system caused by motion during the severe thrust transients also was of concern because of

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(1) Vernon, K. A., Test Stand H-8 System Analysis and Design, Aerojet-General Corporation Report No. 8800-73, 6 May 1966.

the high stresses that would be generated in the thrust chamber at its interface with the test facility. Finally, the steady-state vibration forces and maximum normal operating forces also were of concern because their superimposition on steady-state loads could result in stresses that exceeded safe design limits.

As a result of the analysis, certain changes were made to the propellant feed line support system. These changes, which are described in detail below are summarized in Table I. First, the facility thrust chamber valves were rigidly anchored to the concrete foundation of the test stand. The maximum thrust load generated by a line rupture downstream of the valve was calculated to be 160,000 lbf. The valve support was designed to react this thrust load along the axis of the valve or as a moment and shear force in the event that the line ruptured below the first downstream elbow.

Second, the propellant-line safety valves located near the run vessel were guided and restrained to react the load resulting from maximum propellant acceleration due to a rupture of the downstream line. When the maximum thrust load of 160,000 lbf was applied to the run vessel outlet at its elbow, stresses were created in the run vessel which were greater than those allowed by ASME code. Consequently, the restraint was applied at the valve because this was the only practical point of connection between the propellant piping and an adequate foundation. Thermal expansion and contraction between the line safety valve and the vessel outlet required a valve restraint capable of telescoping. The final load link between the test stand foundation and the valve body was a damper constructed from a commercial hydraulic cylinder and a flow-restriction orifice.

Third, the propellant lines at the thrust chamber assembly/test facility interface were structurally linked to the thrust-measuring frame. This modification resulted from several studies. A transient response study of the thrust measurement system for the predicted start transient was made to define the maximum acceleration of the thrust chamber assembly. Also, a vibration analysis of the thrust chamber assembly and propellant feed lines indicated the maximum relative deflections of that system during the thrust transient. Finally, the results of propellant line vibration analysis, when combined with the results of the full-scale deflection and stress analysis of the thrust chamber assembly propellant torus-manifold, revealed that the expected relative motion of the system during the start transient induced unreasonably high stresses in the propellant torus. Because of this, it was necessary to redesign the structural link to act also as a damper. The oscillating nature of the forces at the thrust chamber assembly, however, dictated that double rod-end pistons be used at this position, and a separate study and full-scale tests were performed to accurately predict the spring/damping characteristics of the dampers. This study produced a practical design approach for future applications and revealed the significance of a high-pressure precharge to the hydraulic fluid to ensure positive damping for small deflections across the dampers.

TABLE I

RESULTANT CHANGES OF DAMPER STUDY

ITEM	RESTRAINT	CONCERN
FACILITY TCV'S	RIGIDLY ANCHORED	BROKEN LINE FORCE (160,000-LB THRUST)
TANK SAFETY VALVES	HYDRAULIC DAMPER	BROKEN LINE FORCE (160,000-LB THRUST)
PROP. LINES - TCA INTERFACE (LINKED TO THR. MEAS. SYSTEM)	HYDRAULIC DAMPER (DOUBLE ROD END)	COMBINED VIBRATION AND NORMAL OPERATING FORCES
PROPELLANT LINES (VARIOUS LOCATIONS ALONG LINES)	DAMPERS AND TRAVEL LIMITERS	BROKEN LINE
PROPELLANT LINES (POINTS OF MAXIMUM DEFLECTION)	DAMPERS	GENERAL SAFEGUARD
GAS LINES	STRUCTURAL RESTRAINTS	GAS FLOW DYNAMICS

Fourth, the propellant feed lines between the facility thrust chamber valve and the TCA were restrained to react against a total and instantaneous line failure at any station in that line segment. This restraint was provided by the dampers between the thrust system and a propellant piping and by additional supports to prevent uncontrolled travel of the ruptured line. Again a hydraulic damper was used as a structural link. This requirement to restrict the motion of the propellant line resulted from the failure analysis of the Test Stand C-9 full-scale test. In that instance, the unrestrained propellant line destroyed the primary deluge header and damaged several major test stand structural members.

Fifth, dampers were used to restrain the propellant feed lines between the thrust chamber valve and the run line safety valve as shown in Figure 4. These dampers were placed at points of maximum deflection as determined from the results of a vibration model analysis of the propellant lines. A finite forcing function was not defined; however, the dampers were added as a general safeguard rather than as a specific remedial action.

Sixth, the gas pressurization system was rerouted and reanchored. Based on Test Stand C-9 experience, it was obvious that the maximum dynamic loads on the 14-in. diameter pressurant-gas transfer piping between the gas storage bottles and the servo-controlled, pressurization valves at the propellant run vessels had been underestimated. Re-analysis of the existing pipe system with maximum gas momentum loads confirmed the need for a new system of anchors. These anchor requirements, in turn, required that the line be relocated for structural support.

The effectiveness of these dampers was verified during two activation checkout tests. Propellant system flow checkout tests were made using liquid nitrogen at rated conditions and with valve sequence and timing that simulated actual firing conditions. Accelerometers, strain gages, and linear potentiometers were monitored during these tests. Analysis of the resultant data indicated that there were no dynamic problems associated with these test conditions. During dynamic calibration tests which were made primarily to determine the natural frequency of the thrust measurement system, the same propellant system instrumentation was monitored. These tests were made with the propellant lines at both ambient and cryogenic temperatures with and without pressure, and with the dampers connected and disconnected. Again, a comparison of the data verified the effectiveness of the dampers.

B. THRUST MEASUREMENT SYSTEM

Determination of the specific impulse developed by the thrust chamber assembly was one of the prime test objectives. To meet this objective, an accurate thrust measuring system was essential. Achievement of this goal, however, was of major concern because of the hardware size and thrust rating for the M-1 Engine.

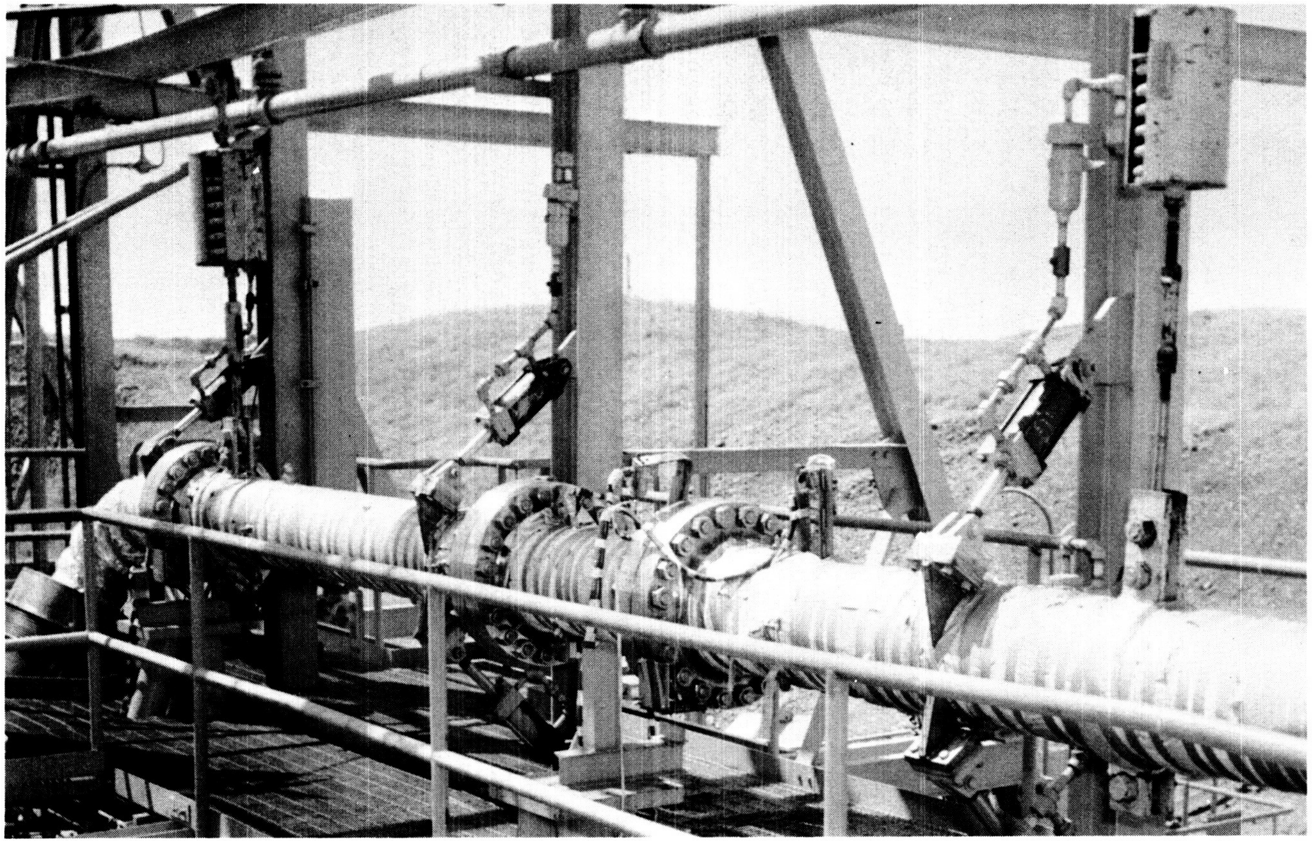

Figure 4. Line Dampers of Test Stand H-8

Design objectives for the thrust measurement system were to provide maximum accuracy and repeatability, to support the M-1 thrust chamber assembly under normal firing conditions and under unpredicted non-axial loadings which could occur at chamber burn out, to provide an integral calibration system, and to make the handling and adjustment of large system components such as flexures and load cells as easy as possible. The initial design included universal-type flexures to minimize the effect of bending and shear on load-cell measurements. These large, commercial flexures failed during fabrication-testing; consequently, they were replaced by a single, simple rod flexure which acted as the load link between the thrust-measuring cell and the thrust block. The rod flexure also was instrumented to provide thrust measurement data, which was found later to correlate closely with the thrust data measured by the standard commercial load cell.

Both static and dynamic thrust measurement calibrations were made. The static calibrations were made with the propellant system pressurized and at cryogenic temperatures to duplicate test conditions. These calibrations were used to determine system bias and repeatability. A servo-controlled, hydraulic jack was used to simulate the load during these calibrations, and the control system was close looped with the calibration load cell to permit the use of convenient and repeatable calibration techniques.

The dynamic calibrations were performed to determine the natural frequency, damping ratio, and linearity of the system as well as to establish the effectiveness of the propellant system dampers. This calibration was made using a calibration jack to preload the system and instantaneously removing the load through the failure of a rigid load link at a prescribed load.

Results of a dynamic calibration proved the propellant line gimbals to be effective in isolating the thrust system from movements of the propellant lines caused by severe pressure and temperature changes. The natural frequency was determined to be 19 H_z, somewhat lower than the calculated value of 23 H_z. The free vibration of the stand was found to have a rapidly decaying frequency and amplitude, indicating that the many mechanical joints of the system acted as highly nonlinear springs and dampers which lowered the frequency and increased the deflection.

The calibrations established the static force measurement accuracy of the thrust measurement system at $\pm$0.5%-3 sigma.

Hoy, Close, and Vernon described the H-8 thrust measurement system and the load-cell calibration facility installed to support this system in NASA report CR-54793.[2]

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(2) Hoy, W. A., Close, J. R., and Vernon, K. A., 1.5 Million Pound Load Cell Calibration and H-Area Thrust Measuring System, NASA CR544793, 27 June 1966.

C. LIQUID OXYGEN FLOWMETER CALIBRATION

Calibration of the 14-in. liquid oxygen flowmeter in the working fluid was considered necessary to assure the highest possible confidence in the data needed to calculate performance. Because Aerojet-General did not have facilities to calibrate this flowmeter in the flow rate range of 3000 lb/sec, it was calibrated at NASA/MSFC. A F-1 turbopump test stand containing a number of liquid level probes in a time-volume system was used for the calibration. Calibration factor uncertainty was estimated to be $\pm 1\%$. This calibration work provided substantiating data on the water-to-liquid oxygen calibration factor shifts for meters of this size.

The flowmeter calibration together with the prediction of other instrumentation uncertainties and the thrust system calibration described earlier allowed greater confidence in the prediction of specific impulse to $\pm$ 1% -3 sigma.

D. CONTROL SYSTEM-COMPUTER CHECKOUT

Automatic control systems were used to establish and maintain fuel and oxidizer tank ullage pressures, hydrogen mixer gas flow rates, and thrust chamber valve positions. Design of these control systems encompassed the simultaneous analysis of each individual control loop because of the dynamic interactions which occur in a complicated test stand for thrust chamber assembly test.

A sequence of logical steps was followed in the design of the total control system. First, a system mathematical model was generated by applying known laws of physics, fluid dynamics, and the thermodynamics to the processes that occur during test stand and hardware operation. The final mathematical model took the form of a set of coupled differential equations which related applicable test facility and hardware parameters. Second, a piping analysis was made to determine appropriate static and dynamic piping parameters such as hydraulic resistance, pipe volumes, and acceleration terms. These physical quantities became constants in the mathematical model. Third, the mathematical model was programmed for simulation using an analog computer. During computer simulation, the control system stability and controllability characteristics were developed together with suitable start transient characteristics. Fourth, the resulting control and sequence criteria were mechanized through the programming of an analog-digital sequence unit installed in the test control room. In essence, the sequence unit was an on-line hybrid test programmer which had been designed to accept process status information from test stand transducers and facility sequence units. The programmer was used to interpret and process this information and then to control the individual servo-control loops by generating appropriate command data. In addition, the programmer was designed to detect impending malfunctions of the facility, hardware, or servo system, and to either override the defective system or to terminate the test.

In addition to engine simulations, the analog computer was used in the design of the tank pressurization control system. The servo-operated, tank pressure-regulating valves of this system were coupled with an electronic process controller unit having closed-loop feed-back circuits which monitored system pressures, flow rates, fluid temperatures and valve positions. This process control system operates as a "computer sequencer," pre-programming analog functions and controlling digital functions.

After the control systems had been designed and installed, a portable analog computer was connected to the facility valves, instrumentation and process control system and a series of simulated dry-run test firings were performed to check for stability and performance. This procedure provided a completed closed-loop verification of the entire system in that all valves and controls were actually operated. This dry-run checkout was advantageous in that the system was tested without the expenditure of propellant, personnel can visually check the operation of facility components safely, and an excellent malfunction analysis was provided for the electronic and mechanical components of the control system.

E. COLD FLOW TESTS

To further extend the advantages of computer-simulated test firings, a progressive series of 33 cold-flow tests were made to evaluate system performance. The objective of these tests was to determine system characteristics such as pressure drops, temperature/transport times, pressurization collapse factors, pressurization rise-rates, process control relationships, dynamic pressure surges, mixer system characteristics, and other functions before actual test firings were conducted. The types of tests and test purposes are summarized in Table II. Liquid nitrogen was used to test the fuel system and liquid oxygen was used to test the oxidizer system. Portions of the gaseous hydrogen injection system were tested using gaseous hydrogen. The fuel system pressurization rise-rate was checked using gaseous hydrogen over liquid hydrogen. Similarly, the oxidizer system rise-rate was checked using gaseous nitrogen over liquid oxygen. And, the flow of the gaseous fluorine ignition system was checked using gaseous oxygen.

The results of these tests indicated the areas of the test facility computer model that needed further refinement. Appropriate modifications were made and the model subsequently was used in problem solution during the initial hot firing series.

The cold-flow tests also revealed other facility activation problems such as liquid oxygen system cleanliness, valve and regulator failures, gas-filter failure under full-flow dynamic conditions, and line restraint failures in the propellant out-flow bleed and dump systems which required correction.

TABLE II

COLD-FLOW TEST SUMMARY

TYPE TESTS	PURPOSE
• FUEL SYSTEM - LN_2 FLOW	DYNAMIC EFFECTS - LINE ΔP TEMPERATURE TRANSPORT TIME
• OXID. SYSTEM - LO_2 FLOW	AS ABOVE - PLUS LOX COMPATIBILITY
• GH_2 MIXER - GAS WITH GH_2 COMPUTER SIMULATED LH_2	MIXER SYSTEM CHARACTERISTICS
• TANK PRESSURIZATION - GH_2 OVER LH_2	RISE RATES - COLLAPSE FACTORS
GN_2 OVER LO_2	DYNAMIC EFFECTS
• GF_2 IGNITION SYSTEM - GO_2 FLOW THEN LOW & HIGH PRESSURE GF_2 FLOW	PASSIVATE SYSTEM-DETERMINE PRESSURE RISE CHARACTERISTICS

This later problem involved an incident where a liquid oxygen line was subjected to a pressure surge believed to be the result of gas bubbles collapsing during line pressurization. This pressure surge caused the flange of the bleed valve to separate from the line and allow high velocity liquid oxygen leakage which ignited causing burning of the stainless steel line and flange. The gas in the system was believed to be caused by improperly located bleed bosses and inadequate bleed time.

The critical adjustment of tank liquid level in relation to pressurization gas collapse factor was identified. Accurate identification of the ullage volume by liquid level measurement at this high operating pressure was expected to be a major problem. Although capacity probes are susceptible to inaccuracies due to dielectric constant changes at high pressure, a Trans-Sonics Model 440 point sensor was used successfully and has proven valuable in the control of this critical ullage volume.

Probably the most serious problem uncovered during this phase was the identification of structural defects in several gaseous hydrogen cascade receivers. These receivers, which were of multi-layer construction with a water volume capacity of 1300 cu ft and a pressure rating of 5000 psi, were supplied by two separate vendors. A thorough investigation of these receivers was made after they failed.(3) The investigators concluded that the failures were caused by high stress concentrations in some of the nozzle welds of the receivers manufactured by the first supplier and longitudinal weld-joint failure in the inner wall of the receivers supplied by the second vendor. Where failure had occurred at the nozzle weld, repair was made. However, the pressure rating on all of the hydrogen receivers was downgraded from 5000 psig to 3500 psig. A change in the design of the nozzle installation has been accomplished and implementation of this change is now in process. It is planned that the operating pressure will revert to 5000 psig after completion of this change. Final disposition of the other receivers has not as yet been made. This reduced pressure rating had a significant effect on the amount of gaseous hydrogen available both for run tank pressurizztion and for injector/mixer system operation; consequently, major system changes were made to compensate for this condition. The mixer line diameter was changed from 6-in. to 8-in. to reduce the pressure drop. Downgrading of the receiver pressure rating also affected the test duration, and the supply of gaseous hydrogen became a limiting factor.

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(3) Laws, J. S., Frick, V., and McConnell, J., Hydrogen Gas Storage Problems, M-1 Engine Program, Aerojet-General Corporation Report No. 8800-67, 15 April 1966.

F. GASEOUS AND LIQUID HYDROGEN MIXER SYSTEM

Design of the mixer system was unique in that a mixer with flow rates of 100 lb/sec of gas and 400 lb/sec of liquid had never been designed before within the industry. Programmed control of the fuel injection temperature was required to achieve an ultimate mixture of 140 $\pm$ 5°R, and then to deramp to 55°R within several seconds. A cutaway sketch of the mixer section is shown in Figure 5.

Simulation of exact test conditions through cold flow tests was judged to be impractical because of the large quantities of hydrogen which had to be disposed of.

The liquid hydrogen flow passages previously had been cold-flow tested to establish the characteristics of the mixer. Next, the gaseous hydrogen system was flow-tested using gaseous hydrogen. The hydrogen flowed from the mixer outlet through the main propellant line and thrust chamber valves and into a long, horizontal burn-off duct which extended beyond the thrust chamber assembly. During this test, a computer was used to simulate the characteristics and responses of the liquid system. In this way, system control was verified to the extent possible under simulated conditions. However, the results of actual test firings dictated that the mixer system be modified. The subsequent changes are described in the section on Thrust Chamber Testing Experience.

G. FACILITY THRUST CHAMBER VALVES

The partial termination of the M-1 Program before the flight-type thrust chamber valves were developed led to the decision to procure commercial facility thrust chamber valves (TCV) for thrust chamber assembly development testing.

The selection of suitable valves was given considerable study. The procurement specifications were quite demanding for an "off-the-shelf" commercial valve. The significant aspects of these criteria were:

1. Size - 14-in. nominal pipe
2. Service - Cryogenic LO_2-LH_2
3. Pressure Rating - 2160 psig (ASA 900-lb class)
4. Pressure Drop - Cv 2600 minimum
5. Leakage - Zero external and zero across seat when closed
6. Actuation Time - Full stroke 0.5 sec minimum

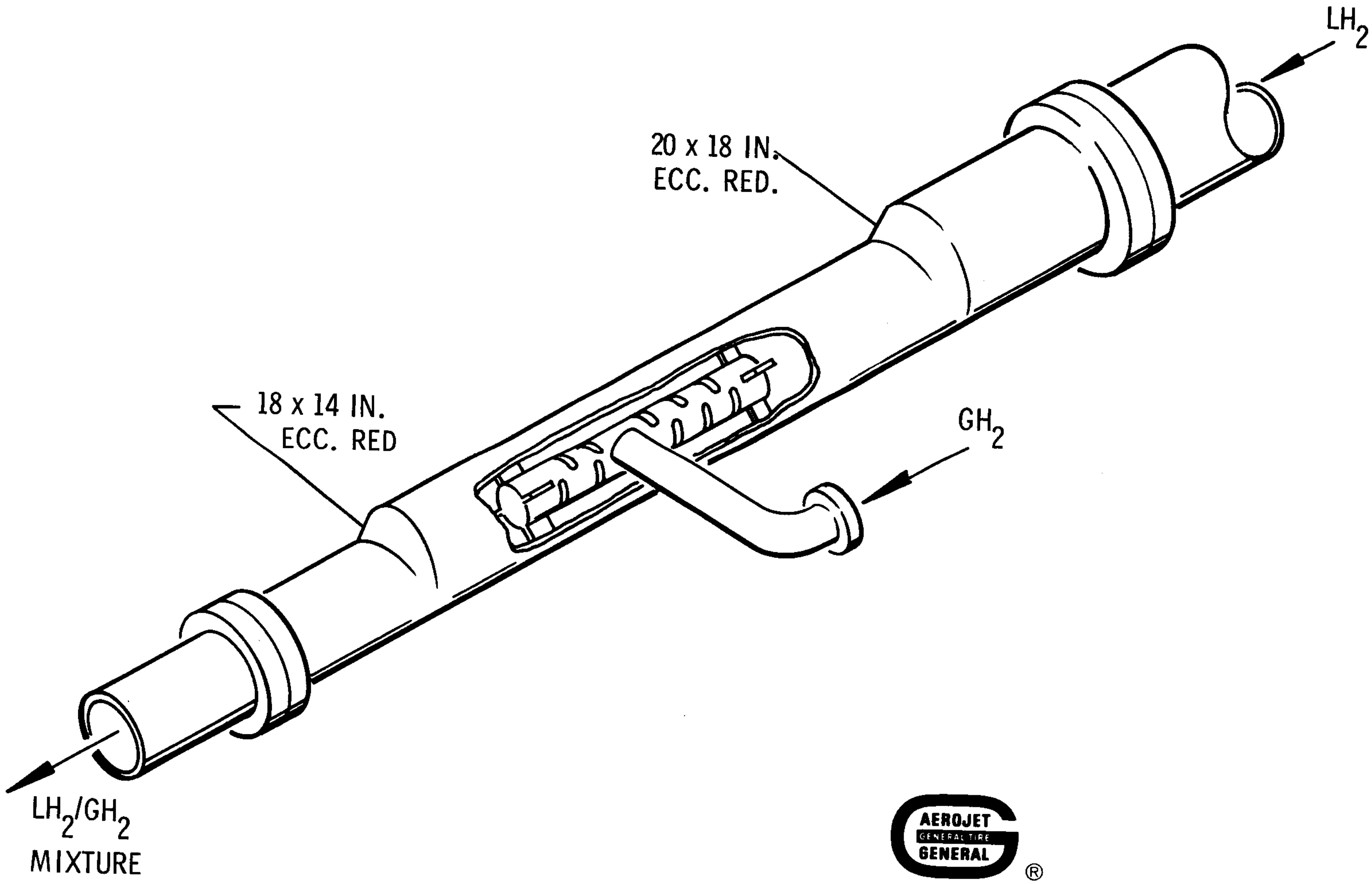

Figure 5. Gaseous and Liquid Hydrogen Mixer Section

Existing 14-in. 900-lb ASA-300 series stainless steel, Y-Globe Annin valves finally were selected because they had been used previously as tank safety valves for another test stand. However, the off-the-shelf valves required modification to satisfy the requirements. The pneumatic actuators were replaced by hydraulic actuators to meet the critical control requirements. The modified actuators had a 12-in. diameter bore, a hydraulic operating pressure of 3000 psi, a new yoke structure for mounting to the valve, a block-type pilot-valve-to-cylinder manifold, and a 1-1/2 in. four-way commercial pilot valve.

The hydraulic supply system required to actuate these valves consisted of two independent 50 gal accumulators and a 3000 psig gaseous nitrogen pressurization system. The independent supply system was designed to prevent adverse interaction between the two valves during actuation cycles.

Various hydraulic fluids were evaluated before final selection was made. Selection criteria were low temperature and liquid oxygen compatibility to minimize the possibility of liquid oxygen system contamination. Initially, Freon TF was considered and tried; however, its lack of lubricating qualities and its low boiling point created problems with pilot valve operation. Next, Pydraul F-9 was evaluated. This fluid had good lubricating characteristics and a satisfactory boiling point; however, its viscosity versus temperature characteristics caused the control of valve timing to vary considerably with ambient temperature. Pydraul 150 was finally selected as the actuation fluid because it corrected all the previous problems and performed satisfactorily. A minor disadvantage of this fluid was its slight degradation of oxygen compatibility as compared with the other hydraulic fluids considered.

An extensive series of dry-run and cold-flow checkout tests were made to verify performance and reliability. During these tests, three problems developed. Pump transfer of the hydraulic fluid from the catch tank to the supply vessels aerated the fluid and caused valve timing variations. This problem was corrected by removing the pump and using a pressure transfer system. Next, the commercial hydraulic pilot valves were found to be extremely sensitive to particular contamination. Pilot valves stuck repeatedly until added filtration was installed and improved hydraulic fluid handling procedures were developed. Larger solenoid valves also were installed on the pilot valves; this modification improved valve reliability considerably. Finally, a lag in initial valve movement was identified as a problem caused by bleeding in the actuation cylinders. To correct this, the cylinders were modified by adding internal passages and external bleed points.

Since their modification, the facility thrust chamber valves have been operated over 2000 cycles during the initial valve and facility checkout and during subsequent hot firings with performance and reliability exceeding expectations. No external leakage has occurred, and only one soft-seat replacement in the liquid oxygen valve has become necessary, undoubtedly due to the fast, 0.4-sec full stroke, actuation time. Erratic pilot valve operation has been the only significant problem encountered.

Nominal valve sticking rates were 0.4 sec for the liquid oxygen valve and 1.9 sec for the liquid hydrogen valve. System response, a significant factor in sequencing, was approximately 0.115 sec from signal initiation to start of valve movement. Repeatability of system activation was approximately $\pm$ 0.01 sec.

H. OTHER PROBLEMS

Three other factors were of initial concern but did not develop into significant problems as initial testing proceeded.

1. Hydrogen Lead Gas

The quantities of hydrogen in excess of 500 lb which flowed through the combustion chamber before ignition were expected to be a potential fire or explosion hazard which could damage the test stand. However, actual tests demonstrated that the velocity of this gas caused ignition at a considerable distance from the chamber in the flame path and downstream of the test stand. Only a sound level spike occurred. No damage ever resulted to the stand or hardware by the hydrogen lead.

2. High-Pressure Leakage in Large Diameter Cryogenic Lines

Special attention was given during system design to the flange joints at locations where component replacement would be necessary. The joints at flowmeter installations, for example, had to be designed to permit periodic flowmeter removal, calibration, and replacement. At such locations, the flange types, gasket material, and torquing procedures were selected carefully. Retained soft aluminum gaskets and 3-1/4 in. flange bolts generally were used. Use of a pneumatic impact wrench and force multiplier to 7500 ft-lb were found to be necessary to achieve the bolting preloads needed. In addition to ambient temperature leak check, an 1800 psi leak check was made whenever the system had been disturbed or its integrity questioned. When such a high-pressure check was required, it normally was made in conjunction with pre-fire procedures to take advantage of system cooldown and to conserve propellants.

3. Sound Level

The far field sound levels generated during M-1 thrust chamber assembly tests were predicted to be acceptable to the surrounding community based upon the coupling factors obtained from smaller scale tests. However, effects due to adverse meteorological conditions made this prediction questionable. The testing conducted to date, which included some testing during the winter months, has indicated that this problem did not develop. A sound measurement study made in conjunction with these tests[4] has affirmed that the sound levels generated during the tests have remained within acceptable limits.

V. THRUST CHAMBER ASSEMBLY TESTING EXPERIENCE

Before undertaking the initial test phase, Critical Experiment Reviews were held with cognizant engineering managers to make certain that both hardware and facilities were in readiness. From the facility standpoint, verification of the starting and shutdown sequence controls, mixer system operation, fluorine ignition system operation, and thrust measurement were of prime concern.

The test plan called for three levels of operation in reaching full thrust. The first level involved operation only up to a chamber pressure of approximately 200 psi to demonstrate the operation of the fluorine start system. During this test, the liquid hydrogen flow through the mixer system was blocked by the injected gas, causing fuel injection temperatures which were warmer than desired. The mixer section was reworked to direct the flow of the injection gas more in line with the liquid flow thereby decreasing the radial gas velocity. In addition, an orifice was added to the main liquid hydrogen line (at the tank safety valve) to "harden" the liquid system. This increased line pressure drop resulted in making the main liquid system less sensitive to downstream changes caused by the mixer gas system. These changes, coupled with a slower gas ramp sequence corrected this condition. The second level was satisfactory operation at the 50% thrust level. This test was followed by a 100% thrust level firing which demonstrated the successful operation of all systems.

Following the tests at full thrust, a series of injector performance tests were made, followed by a series of stability tests which demonstrated the versatility and complex event-sequencing capability of the control system. A typical sequence of events for these combined performance and stability tests is described briefly in the following paragraphs to illustrate this sequencing versatility. Figure 6 provides simplified plots of the critical parameters.

A. START TRANSIENT

Before the actual starting transient sequence was begun, the fuel supply was pressurized to 800 psia and the oxidizer supply to 540 psia to

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(4) Deppe, G. R., and Spataro, S. J., Measurement and Evaluation of Sound Levels From M-1 Thrust Chamber Tests, Aerojet-General Corporation, Report No. 0830:99, 27 June 1967

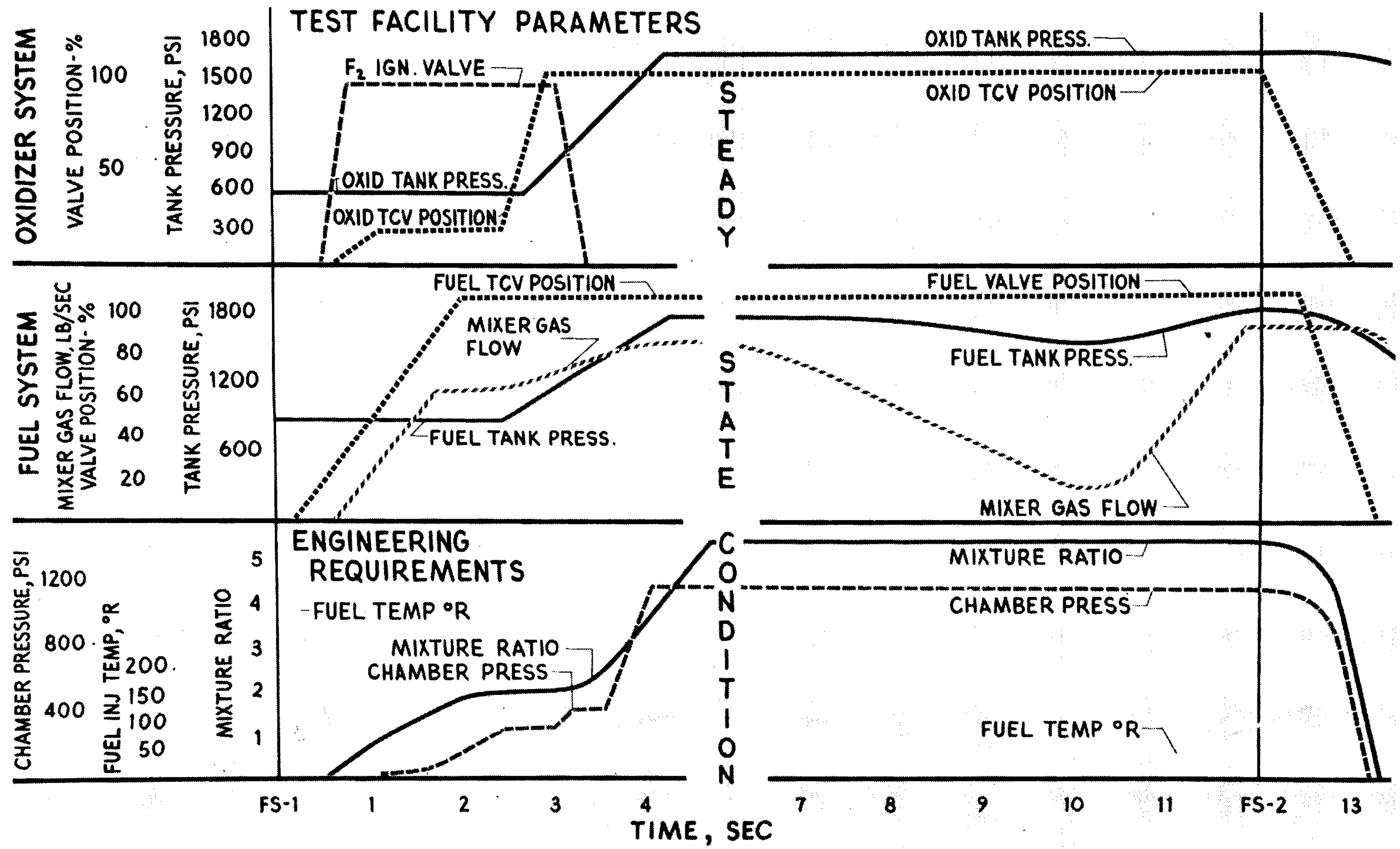

Figure 6. Critical Parameter Plots

ensure positive flow control. In addition, the ignition system was pressurized to 800 psia with gaseous fluorine.

Immediately after fire-switch, fuel flow was controlled to establish and maintain a fuel-rich mixture. As liquid hydrogen flow began, the fuel was warmed to 100-140°R by injecting gaseous hydrogen into the mixer. The flowing fuel then was ignited through a hypergolic reaction with the injected fluorine. After establishing a fuel-rich flame front, low-level combustion was created by oxidizer flow at a low rate through a 6-in. bypass valve. As the chamber pressure reached 200 psig, indicating positive combustion, both fuel and oxidizer systems were pressure-ramped to predetermined levels to achieve full combustion pressure.

Approximately 50 control functions were exercised during this period, and the programmed completion of 20 events was necessary to complete the start transient.

B. STEADY-STATE OPERATION

After the start was completed, steady-state performance was sustained for at least 2 sec to sample all operating parameters for an accurate determination of performance characteristics. The following parameters were closely controlled during steady-state operation within the lmiits indicated, depending on the mixture ratio-performance points desired.

Mixture Ratio	4.0 to 6.5 ($\pm$ 0.2)
Combustion pressure	950 to 1150 psi ($\pm$ 10 psia)
Fuel Flow (LH_2)	350 to 500 lb/sec ($\pm$ 25 lb/sec)
GH_2 Injection Flow	40 to 120 lb/sec ($\pm$ 2 lb/sec)
Oxidizer Flow (LO_2)	2200 to 3000 lb/sec ($\pm$ 50 lb/sec)
Thrust force	0.8 to 1.1 M lbf ($\pm$ 1%) (sea level conditions)

During steady-state operation, several mixture ratios can be obtained by controlling the fuel tank pressure, the oxidizer tank pressure, or both.

C. INDUCED INSTABILITY AND RECOVERY

Following steady-state performance, the amount of gaseous hydrogen injected into the mixer was reduced at a controlled rate (between 2 and 4 sec) to chill the fuel down to as low as 55°R. This was done to determine the exact conditions of propellant temperature and mixture ratio that will produce combustion instability in order to define the stability characteristics of the injector. To further complicate the requirements, the pressure of the liquid hydrogen system also had to be reduced proportionally during this period to closely maintain total fuel flow and mixture ratio.

Once combustion instability occurred, it had to be immediately detected and steady-state performance recovered automatically and rapidly by controlled warming of fuel flow to avoid system damage. This meant that instability had to be sensed accurately and responded to instantaneously. Normally, a flush-mounted water cooled chamber pressure transducer would be used for this application. However, this type of pressure transducer could not be used with the ablative lined M-1 combustion chamber because any liner erosion would cause the hot gases to erode the relative large transducer face. For the M-1 application, a "Helium Bleed Transducer" developed by Aerojet-General during the Gemini Stability Improvement Program(5)(6) was used. This transducer design, which was based on the small passage technique, makes use of helium as the gas medium and a piezo-electric-type sensing element to accurately measure chamber pressure fluctuations during test firings. The latest design of these units has a flat frequency response to 10,000 Hz.

Combustion stability monitors also designed by Aerojet-General were used to sense the pressure oscillations measured by the Helium Bleed Transducers. Application of these monitors was extremely flexible and allowed sensing and adjustment of three variables which were pre-programmed to initiate shutdown. Typical settings of the two units on M-1 tests (one low-frequency and one high-frequency sensing) are shown below:

	Pressure Amplitude psi(P-P)	Frequency Range (Hz)	Minimum Duration of Oscillations to Produce Shutdown
Low Frequency	300	100-700	100 msec
High Frequency	100	600-10,000	30 msec

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(5) Wesley, R.D., et. al, Gemini Stability Improvement Program, Aerojet-General Corporation Report No. SSD-TR-66-2, Vol. 6 Instrumentation, 31 August 1965.

(6) Wesley, R.D., Redding, R.H., Hefner, R.J., Comparison of Instrumentation Techniques for High Frequency Combustion Chamber Pressure Measurements, AIAA Paper 65-360.

D. SHUTDOWN TRANSIENT

Once all test data were acquired, a controlled shutdown of the thrust chamber assembly was begun. First oxidizer flow was terminated. This was followed by the cutoff of liquid and gaseous hydrogen injection flow. This sequence was necessary to avoid an oxidizer-rich, hot shutdown. During the final period of propellant flow cutoff, the supply system valves were sequenced to avoid "water-hammer" pressure surges. Residual flow of oxidizer was dumped upstream of the injector and followed by high-pressure purges into the oxidizer and fuel manifolds.

VI. TEST OPERATIONS EXPERIENCE

Operating procedures have improved with experience and, even though the size and complexity of the H-8 facility represented a new dimension, test performance has been good. Tests have been repeated within a four hour turnaround in several instances. Propellant use rates (a factor highly influenced by test rate and duration) have improved approximately 30% and, because liquid hydrogen is an expensive part of the propellant mixture, this improvement has had a significant influence on program cost. To date, no in-test malfunction has occurred due to facility equipment problems. Several test-firing starts were aborted and several in-test malfunctions have occurred because of human error. It should be noted that in each of these cases a safe shutdown was achieved and no test hardware or stand damage resulted.

VII. FACILITY EXPERIENCE

Test Stand H-8 has been operated for approximately one year in the liquid hydrogen and oxygen testing of thrust chamber assemblies at thrust levels of 1-million lbf. Pretest equipment problems generally have been associated with pilot valves, valve leakage, and flow control-regulator valve galling. Nevertheless, removal, repair, replacement and checkout of these components have been accomplished in one week or less. It should be pointed out, however, that facility problems and maintenance with these large high-pressure systems have been greater in proportion to that previously experienced on smaller, high-pressure test stands having 6 to 8 in. piping systems.

Some of the facility problems that have developed during initial and subsequent testing operations are discussed in subsequent paragraphs.

A. FLOW-CONTROL VALVE GALLING

Pressure-regulating valves, which are the fast-acting, plug, flow-control type, have failed because of internal galling of the non-lubricated, metal-to-metal plug and sleeve. Attempts to correct these failures using various plating techniques such as chrome plating and moly-disulfide coating have not proven totally effective, and continued investigation is needed. A procedure of periodic valve inspection utilizing an external ultrasonic listening device to detect internal binding or galling has been developed to allow continued operation with acceptable confidence. This inspection precludes the time-consuming valve removal and tear-down inspection that otherwise would be required for these large, high pressure components.

B. HIGH-PRESSURE GAS VALVES

The 12-in. and larger high-pressure gas valves (3000-5000 psi) used with gaseous nitrogen and hydrogen generally have not operated satisfactorily because of seal leakage for both manual and remote types. When both the manual valve (which is used to isolate the system upstream of the remote valve) and the remote valve leak, the gas cascade must be vented down to permit repair. This action, however, is expensive and time-consuming. Leakage of these valves is serious, especially that of the gaseous hydrogen system because the pressure in the lower-pressure systems builds up and over-exercises relief valves and burst diaphrams. Also, the leakage of combustible hydrogen gas is a safety hazard to maintenance personnel making repairs.

C. CRYOGENIC VALVES

Repair of valves in the large cryogenic systems also can be costly, especially when failures occur after system chill-down. The warm-up and inert-purge cycles for these large, thick walled (6-in.), vacuum-jacketed vessels and piping systems require several days before the system can be opened and the components removed. To preclude valve failure, component reliability for these systems is critical and indicates the need for design selection of only prequalified components of the best possible design.

A specific problem area has been leakage of valve bonnet seals and packings. Because of long lead procurement, some existing valves were used which did not incorporate specific cryogenic valve design criteria. Here inadequate valve bonnet extension resulted in insufficient isolation of the seal from the cryogenic fluid. Electrical heater-coils have been used around the seal in the interim to remedy this condition. Nevertheless, with this solution valve preheat is necessary prior to system cool-down to maintain the necessary gas insulating pocket between the cryogenic liquid and the seal.

D. LARGE HIGH-PRESSURE FLANGE MAKE-UP

Mating of large flanged components and spool sections of close-fitting tongue-and-groove configurations is a difficult and awkward operation. This is especially true when large cranes and power compression devices are necessary to perform this operation. The "hand-feel" fit normally experienced with smaller flanges is lost, and misalignment during make-up can result in serious damage to flange faces. A tapered ASME tongue-and-groove joint would be ideal for this application; however, such a joint configuration is not commercially available. An alternative solution is the use of alignment pins, although these are somewhat difficult to adapt to standard flanges.

E. FAIL-SAFE MANIFOLDS

Early in the operation of Test Stand H-8 it was found that electrical failure during servo-operated, flow-control valve operation caused the valves to move to an indeterminate position and could over-pressurize the downstream systems or cause the loss of mixture ratio control. To preclude this situation, a "fail-safe" hydraulic manifold was procured. This manifold applied positive closing pressure to the valve whenever control pressure or power was lost.

F. CROSS-CONNECT POTENTIAL, ELECTRICAL CONTROLS AND INSTRUMENTATION

Inter-connection of data acquisition and control instrumentation was found to introduce signal errors to the control system because of spurious feedback signals originating in unrelated data acquisition circuits. This condition was caused by the sensitivity of the complex test programmer and controller. To eliminate this problem, control and data acquisition systems, including the end measurement transducer, currently are isolated completely from each other.

G. FLUORINE CHECK VALVES

Operation of the fluorine ignition system has verified the adequacy of the rigorous design and operating procedures originally established for its operation. Experience with this relatively high pressure system (800 psi) has revealed that conventional, in-line check valves lack the necessary reliability at high velocity flow rates. One of the four check valves used to isolate each fluorine injection probe burned out during the flow check. It was decided to remove all check valves and to substitute continuous high pressure gas purges. Because the fluorine system interfaces with the combustion chamber, these purges provide the only isolation of the high pressure, hot combustion chamber gas from the reactive fluorine system. An adequately designed, facility-type check valve could serve to protect the critical cleanliness requirement of the fluorine system when such a check valve becomes available.

H. CABLE PROTECTION

During testing the "short-barreled," sea level configuration of the M-1 combustion chamber displayed unusual high-temperature gas back-flow and recirculation characteristics external of the chamber. This condition exposed the control and instrumentation wiring at the chamber interfaces to extreme temperature conditions. For adequate protection, the cabling was wrapped with an aluminized, heat-resistant rubber tape manufactured by Minnesota Mining and Manufacturing Company. This tape provided total protection under these severe conditions.

I. FLUID DECELERATION EFFECTS

The non-linear stroking speed and the plug configuration of the liquid-oxygen tank safety valve combined to produce fluid deceleration forces at test shutdown which were much greater than originally anticipated. The plug configuration was designed to give rapid opening flow. Non-linear closing resulted from increased valve closure speeds at the end of the closing stroke because the pneumatic actuation system had less control than the hydraulic system used for the same type, thrust chamber valves. This condition caused the stoppage of approximately 50% of the liquid oxygen flow (1500 lb/sec) in the last 25% of valve travel, and the resultant forces moved the liquid oxygen tank mount and valve restraint. Replacement or rework of this valve was not possible because of the long procurement cycle; thus, the valve restraint was redesigned, based upon actual test data, to react this rapid fluid deceleration force. A solid inter-tie to the main test stand structure was provided which incorporated a connecting link that was manually installed after the system cool-down movement had been positively achieved, thus providing restrain for the valve. This link was then removed after a test series prior to the system warm up.

VII. CONCLUSIONS

The testing of thrust chamber assemblies for large-scale cryogenic engines, which appeared to be a monumental task at the outset, has developed into a routine procedure. Over and above this, testing performance has been improved significantly through the application of current state-of-the-art innovations to the facilities.

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